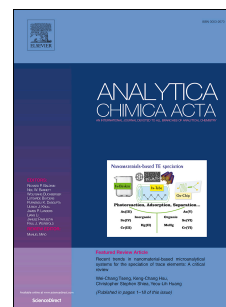


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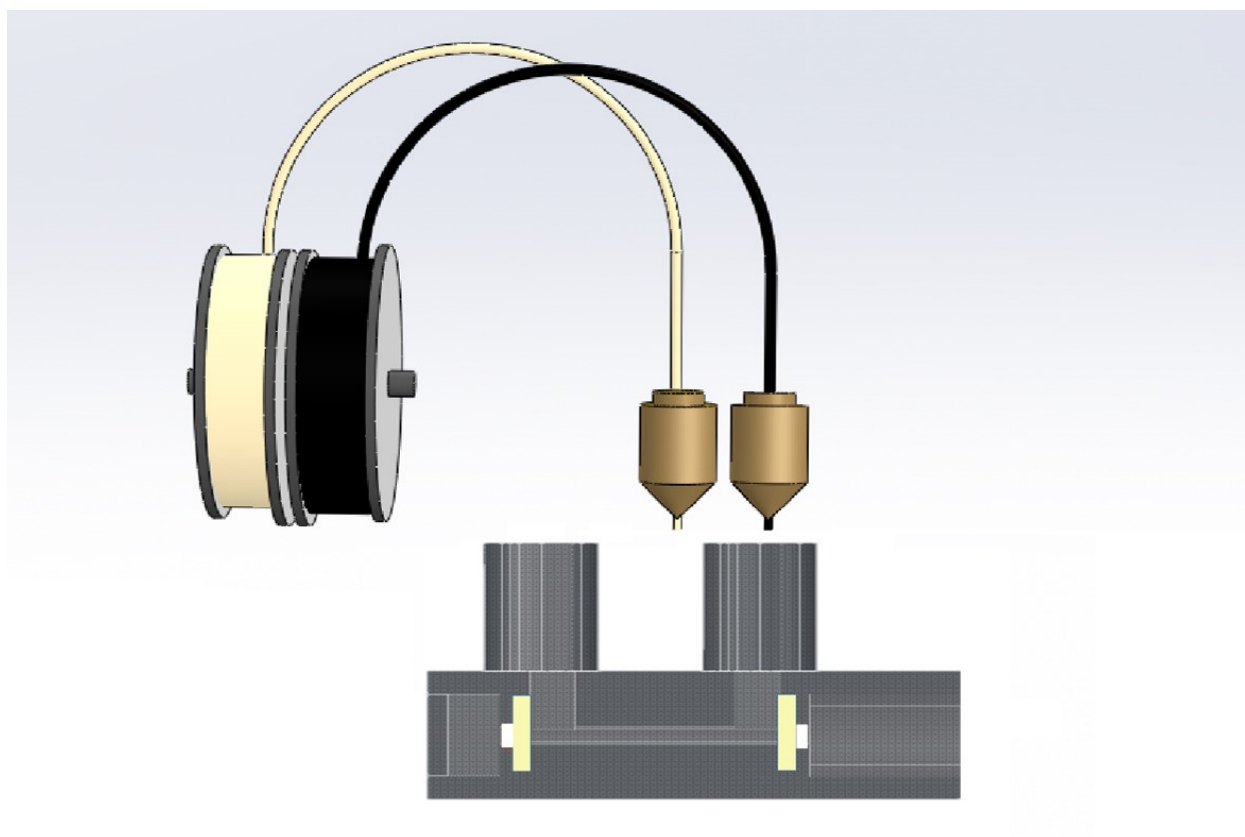
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One step multi-material 3D printing for the fabrication of a photometric detector flow cell

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Keywords

3D printing; fused deposition modelling; light emitting diode; photometric detector flow cell; straylight; effective path length

Abstract

Optical detection is the most common detection mode for many analytical assays. Photometric detection systems and their integration with analytical systems usually require several assembly parts and manual alignment of the capillary/tubing which affects sensitivity and repeatability. 3D printing is an innovative technology for the fabrication of integrated complex detection systems. One step multi-material 3D printing has been explored to fabricate a photometric detector flow cell from optically transparent and opaque materials using a dual-head FDM 3D printer. Integration of the microchannel, the detection window and the slit in a single device eliminates the need for manual alignment of fluidic and optical components, and hence improves sensitivity and repeatability. 3D printing allowed for rapid design optimisation by varying the slit dimension and optical pathlength. The optimised design was evaluated by determining stray light, effective path length and the signal to noise ratio using orange G. The optimised flow cell with extended path length of 10 mm and 500 μm slit yielded 0.02 % stray light, 89% effective path length and detection limit of 2 nM. The sensitivity was also improved by 80% in the process of optimization, using a blue 470 nm LED as a light source.

1. Introduction

Optical detection is a common mode for many analytical analyses [1-3]. In recent years, there has been an increasing demand for the customisation and integration of detectors/ detection assemblies within microfluidic systems due to low volume sample handling and faster response time advantages. Integrated microfluidic systems allow sample introduction directly to the detection techniques thus introducing automation through minimising sample handling and human intervention. Customised detection assemblies for photometric detection [4] and combined three detection methods (contactless conductometric, photometric and fluorometric) for single point simultaneous detection of three signals [5] have been studied. However, the detection assemblies usually require various assembly parts and manual alignment of the capillary/tubing which limits the sensitivity and repeatability of the method. Therefore, the integration of the channel within the detection assembly and extended optical path length will result in improved sensitivity and repeatability of photometric detection. A photometric flow cell with integrated channel and extended path length (200 mm), resulting in four-fold increase in sensitivity, has been reported previously [6].

The flow cell design offers flexibility in adjusting the path length. However, it requires assembly of several parts including supporting blocks for housing the LED and photodiode; glass cylinders to seal the channel ends and provide the transparent detection window inside the body for the light to travel from the light source through the sample to the detector; and inlet and outlet tips, joined to the channel body by melting a small surface using a torch [6]. The manufacturing and manual assembly of various parts of the flow cell is a labour intensive and time-consuming process and is prone to error due to manual intervention. Furthermore, traditional machining methods (e.g. CNC milling) used for manufacturing detection assembly/flow cell are time consuming, expensive and not suitable for repetitive design modifications.

3D printing/additive manufacturing converts 3D models into a physical object in a one-step manufacturing approach that can significantly quicken the innovation and product development cycle [7-14]. Recent improvements in 3D printers and the development of a wider variety of materials has seen an increase in the use of this technique for detectors [15-17], electronics [18, 19] and pneumatics valves and pumps [20, 21]. 3D printing has been used previously for the fabrication of detection assemblies for photometric and fluorescence detection due to its ability to create complex hollow structures which is otherwise

challenging to achieve using traditional manufacturing techniques [4, 15]. Modern multimaterial 3D printers are capable of simultaneous printing with different materials provide a great opportunity for the integration of components of varying functionality into a single object. Recently, multimaterial stereolithography (MMSL) 3D printers consisting multiple resins and multimaterial inkjet-based printers have been developed. However, currently, both have limited material options with most of the materials not completely opaque, are costly and time-consuming. Additionally, intricacy in moving the printed object between the resin containers in case of MMSL and support removal requirement of polyjet printing make them unsuitable for various applications.

Fused Deposition Modelling (FDM) benefits from a wide range of available materials including optically opaque filaments, and the availability of low-cost multiple nozzle FDM printers allow combination of different materials with varying functionality and properties into a single object [12, 15, 22-25].

In our previous report, FDM 3D printing was used to fabricate a LED detector body containing a slit for photometric detection that could be positioned on any external capillary or tubing with an outer diameter (o.d.) from 360 μm to 10 mm [4]. Equipped with a LED and photodiode, the detector's performance was equivalent to commercially available detection interface, and served well for on-capillary detection, primarily exploited for traditional fused silica o.d. 360 μm capillaries used typically in CE or capillary LC.[4] In a different and complementary approach to our previous detector design, alternative designs of flow cells with the liquid in contact with the 3D printed cell offer some advantages worth investigating.

Here we report on the use of multi-material fused deposition modelling (FDM) 3D printing for manufacturing a single piece flow cell; consisting of an integrated slit and flow channel in an opaque body, and a transparent detection window; for photometric detection. The opaque device body and transparent detection window were printed simultaneously using a dual-head FDM 3D printer with opaque and optically transparent materials. Integration of the flow channel, the detection window and the slit in the single device eliminated the need for manual alignment of fluidic and optical components, and hence improved repeatability. 3D printing allowed for rapid design optimisation by varying the slit dimension and optical path length. The optimised design was characterised by determining stray light, effective path length and the signal to noise ratio using orange G.

2. Materials and method

2.1. Chemicals and detector characterisation

Orange G (1-phenylazo-2-naphthol-6,8-disulfonic acid disodium salt) of Standard Fluka quality was obtained from Fluka (Buchs, Switzerland). Water was purified from deionized water using a Milli-Q water purification system (Millipore, Bedford, MA, USA).

A series of standards was prepared by serial dilution of stock solution of Orange G. The absorbance was calculated by the data acquisition system from the signal as its logarithmic function. The detector flow cell channel was first flushed with water and then with the Orange G standards. The flow was stopped, and the absorbance was measured under static conditions. Each test solution was measured in triplicate and in order of increasing concentration. From the sensitivity vs absorbance curve, the effective path length and percentage of stray light values were calculated. Determination of stray light by filling the detection cell with a highly absorbing solution is well justified in principle, well established and has been used previously [4].

2.2. Designing and fabrication

The computer aided design (CAD) of the detector flow cell was made by using Inventor Pro. An FDM printer (Felix 3.0, Felix robotics, the Netherlands) used for the fabrication of the flow cell. Polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) are the two most commonly employed materials for FDM printing. PLA material and transparent PLA (Matter Hackers, CA, USA) was used to print the flow-detector as our testing solution consisted of orange G prepared in aqueous solvent. However, ABS or polypropylene, potentially more resistant to hydrolysis and a range of chemicals (e.g. aqueous solutions of acids, alkalis, and alcohols) should be employed for the fabrication of flow cell to be used under harsh chemical conditions [8, 26]. Flow cells were printed from the STL files using the printer's proprietary software. The extruder temperature was 210°C, the print bed was 70 °C.

Layer thickness plays a crucial role on the surface properties of the printed object. FDM printers allow printing layers ranging from 50 µm to 500 µm. Objects printed with layers of 50 µm thickness will take longer to print and will result in rough surface due to the presence of large number of layer grooves. Therefore, to print the transparent part of the flow cell, a layer thickness of 150 µm was chosen to provide a relatively smooth surface because of the presence of fewer number of layers and therefore fewer grooves. Based on our previous work on printing orientation optimisation for the fabrication of slit for photometric detection

assembly, the printing direction was kept parallel to the slit i.e. XY direction. The printing speed was kept at 50 mm/ sec.

2.3. Instrumentation

The detection system comprised of a multicolour (Red 630 nm, Blue 470 nm, Green 525 nm) LED (5 mm, 30 mA maximum steady current) from LigCom Group (Glen Cove, NY, USA) and a highly integrated light-to-voltage optical sensors, combining a photodiode (PD) and a transimpedance amplifier on a single monolithic integrated circuit (TSL12S-LF) from Mouser Electronics (Kwun Tong, Kowloon, Hong Kong). The PD was connected to a transimpedance amplifier and the output is directly proportional to the light intensity and the absorbance digitally obtained. Labview (SP1 2011) software was used for control of all components from National instruments (Macquarie park, NSW, Australia). An I/O module (NI-DAQ 6008) with 12bit ADC resolution was used with data collected at a frequency of 100 Hz and numerically averaged to 1 Hz. For the LED, negative cable of the 240V AC in 12V DC out power supply was connected into metal oxide silicon field effect transistor (MOSFET). The current regulator (LM317LF) from Taejin Technologies Co., Ltd. (Seo, Daejeon, South Korea) was connected to the connected to the Trimming potentiometer (3386-3/8) from Bourns (Riverside, CA, USA)

Dino-Lite microscope (AM4113-FV2T) was used for capturing the micro scopic images of the channel path length from Dino Lite (Joondalup, WA, Australia). Fig.S.1 shows the complete circuit diagram of the instrumentation.

3. Result and discussion

3.1.1. Flow-cell design and general considerations

The key elements for the flow cell design include: (i) minimum or no assembly supporting repeatability and robustness, (ii) housing for the LED and photodiode, (iii) integrated slits to reduce stray light and provide optimum optical performance, (iv) transparent detection windows at a pre-defined distance determining the optical path length, (v) fluidic ports for interfacing at the flow cell's inlet and outlet. These were addressed by designing and 3D printing the entire flow cell including all the functional parts integrated into a single device body. A multi-material 3D printer with dual nozzles allowed printing of the device body with an opaque material, black PLA, and the transparent detection window, transparent PLA. The black opaque material was chosen to provide an opaque housing for the photodiode to allow minimum or no ambient light to the photodiode thus reduced stray light. Similar approach has been utilised previously to avoid the ambient light, by encasing the photometric

detection assembly into the opaque black silicon material[27]. Integration of the slit and flow channel in a single body reduced the time required for setup compared with our previous report, where positioning of the tubing within the optical path was critical to reduce stray light, maximise effective path and produce a high signal to noise ratio to give optimal optical performance [28]. In our new design, the cavities for the LED and photodiode were positioned on each side of the slit which facilitated quick insertion of the LED and photodiode on the device, with the path length defined by the length between the slits. The CAD design and a photograph of the 3D printed photometric detector flow cell are shown in Fig.1.

To examine the repeatability of the cell, four cells with path lengths ranging from ranging from 7.5 to 15 mm, were printed three times ($n=3$). Transparent material (PLA) was employed for the fabrication of cells to allow visualisation of channel length using a coloured dye. Each channel length was entirely filled with the coloured solution of a dye and was observed under the microscope. IOS capture software was employed for precise measurement of the channel length. Fig. S.2 shows the microscopic images of the channel length filled with the dye solution. The data in Table S.1 shows good agreement between the design and printed path lengths, with on average, the printed length being ~ 99% of the design length. The repeatability of each design was also acceptable, with an error of 0.06 to 0.27 % RSD. These results demonstrate the excellent repeatability of the 3D printed cells and a close agreement of the designed parameters with the printed parts for our device.

3D printers print the object layer-by-layer and transparent walls will have impression of the layers. To examine the effect on optical performance the optical characterization for the flow cell including transparent detection window was performed. Orange G has been commonly used in previous studies as the model analyte for the characterisation of the optical detectors/ detection methods [29, 30], therefore it was chosen as the test analyte for the characterisation of the newly developed flow cell.

3.1.2 LED emission spectrum

The prerequisite of choosing a LED as a light source that its emission spectrum and the absorption spectrum of the compound under study should present a wide overlap [6, 31]. To confirm that orange G is a suitable compound spectrally matching the blue LED, the absorption spectrum of orange G and emission spectrum of the LED were recorded, which are shown in Fig.2. Two spectra present a wide overlap with the maximum of LED emission measured at 466 nm, and the maximum absorption of the orange G compound is measured at 472 nm. These results showed that 470 nm blue LED could be chosen as the light source

for photometric detection of the Orange G, therefore this compound was chosen for the characterization of the flow cell.

3.2. Comparison and optimization of optical performance of the detector flow cell design

Practically, the performance of a photometric detector is determined by the signal to noise ratio that can be obtained. Optimum performance is associated with low stray light and high effective optical path length, which are influenced by the actual detection cell length and slit size. Therefore, the performance of the 3D printed photometric flow cell was characterised by measuring the % stray light and effective optical path length. Flow cells with various slit sizes and optical path lengths were characterised to investigate the device with optimum performance. The signal to noise and detection limit were determined using orange G solution.

Theory

The flow cell was designed to accommodate a silicon photodiode on one side and LED on the other, allowing optimal use of the radiation emitted by the blue LED. Flow cells with various optical path lengths (7.5–15 mm) and slit sizes (200–500 μm , squared shaped slits with 300 μm depth i.e. 200 x 200 x 300 to 500 x 500 x 300) were fabricated, further details on printing parameters and slit geometry are provided elsewhere [4]. Each flow cell was assessed on agreement with Beer–Lambert law Eq. 1 [32, 33]. Although the Beer-Lambert-Bouguer law used in the form of Eq. 1 is valid for monochromatic light. The influence of non-monochromaticity of LED emission spectra has been examined in detail and shown that its effect on detection linearity is negligible [32, 33].

$$A_{real} = \log \frac{I_0}{I} = \epsilon \cdot \ell \cdot C \quad (\text{Eq.1})$$

where (A_{real}) = absorbance of the solution; I_0 = Intensity of light incident upon the sample cell; I = Intensity of light leaving sample cell; ϵ = molar absorption coefficient; c = concentration of the sample; ℓ = path length of the cell.

The sensitivity (S), the signal of the analyte per unit concentration, is calculated by dividing the measured absorbance (A_{eff}) with the concentration (used for absorbance measurement) of the sample [33, 34],

$$S = \frac{A_{eff}}{C} \quad (\text{Eq.2}).$$

The effective path length, ℓ_{eff} , was determined by rearranging the Beer-Lambert law. The plot of S (A/C) vs (A_{eff}) Fig.2 could be used to determine the effective path length by extrapolating the graph to zero absorbance or dividing this S by ϵ . [4].

224 The Following equations were used for calculations;

225 $A = \epsilon \cdot \ell \cdot C$ (from Eq. (1)) (Eq. 3),

226 $\ell = \frac{A}{\epsilon \cdot C}$ (Eq. 4)

227 $\ell_{eff} = \frac{S}{\epsilon}$ (Eq.5)

228

229 Any light coming from the LED outside of the cell, is not going to be detected by the detector, which
 230 is the case for stray light. The stray light – detected light that does not belong to the bandwidth of
 231 the selected wavelength – was determined as the percentage relative to the incident light and is
 232 calculated from the maximum absorbance (A_{max}) of the analyte. [4, 5]

233 $stray\ light\ \% = 100 \times 10^{-\left(\frac{A}{A_{max}}\right)}$ (Eq. 6)

234 3.2.1. Optimisation of slit size

235 In photometric detection, the slit plays a vital role in light collimation and optical performance [4, 33,
 236 35, 36]. Ro et al. reported a significant increase in effective path length by introduction of a slit when
 237 compared to a similar detector design without a slit [36]. In this work is we used an opaque channel
 238 with transparent detection window to see the effect on sensitivity, effective path length and stray
 239 light. In this design the LED housing was made in a way so that LED was inserted inside the opaque
 240 long housing which minimise the stray light and black opaque walls of the channel absorb stray light
 241 as well. To pass the light, transparent detection windows were printed on each end of the flow cell,
 242 with a small opaque slit printed adjacent to the transparent material. Square slits ranging from 200-
 243 500 μm were incorporated on both ends of the flow cell and their effect on detector performance
 244 was studied by determining the linearity, effective path length, and stray light of Orange G as
 245 previously reported [31, 33, 37]. A flow cell with 10 mm optical path length (average channel length
 246 of each flow cell after 3D printing ($n=3$) is 9.98) was used for optimising the slit size. The detector
 247 performance was determined by measuring the absorbance of Orange G over a concentration range
 248 of 0.0097 to 20 mM by Eq.1, which was used to calculate the sensitivity. The sensitivity calculated by
 249 Eq.2 was found to be in the range of 13046 to 16683 AU.L/ mol. for the 200 to 500 μm slits.

250 The Beer-Lambert law allows for determining the effective path length by extrapolating the S vs A
 251 graph to zero absorbance and dividing this by ϵ (18546 L.mol⁻¹cm⁻¹); obtained from Eq.5. For a flow
 252 cell with 10 mm path length, effective path-lengths of 7.1 mm (72.5 %), 7.3 mm (74.53 %), 7.8 mm
 253 (79.5 %) and 8.9 mm (90.5 %) were obtained for the 200, 300, 400 and 500 μm slits respectively,
 254 values that are comparable to the literature values for photometric detection systems [4, 33, 36-39].
 255 This is graphically depicted in Fig.3.

The percentage of stray light can also be determined from Fig.3 and was determined using Eq.6. Values for stray light ranged from 0.1 to 0.6 % for the slits ranging from 200 to 500 μm . This is almost a 35 fold improvement in comparison with our previously reported LED based 3D printed photometric detection assembly, where stray light was 3.8 % [4]. This improvement is most likely due to the improved positioning of the flow cell within the optical path and agrees well with previously reported values ranging from 0.6 to 50 % for LED based detectors [36, 38-40].

The final numerical parameter used to characterise the photometric detector performance was the baseline noise. The stability with which the LED and photodiode are positioned affects the vibration, with enhanced stability reducing baseline noise. With the detection limit determined by the signal to noise ratio, decreasing the baseline noise results in a lower limit of detection. The noise ($n=3$) was calculated by estimating the short time variation of the baseline, average value provided in Table 1 and the limits of detection (LOD) for the method were calculated based on a signal to noise ratio of 3. The noise, signal to noise ratio and detection limit were determined for Orange G using the 200, 300, 400 and 500 μm slit and are given in Table 1, with values comparable to literature reports for similar dyes [41]. It was observed that the slit in this arrangement is reducing the light intensity which could be the reason for the increase in noise values. These results also showed that the slit also has minimal effect of stray light on these extended path length flow cells. Based on these results, a 500 μm slit provided the best optical performance with highest effective path length, minimum stray light and lowest limit of detection.

3.2.2. Optimisation of path length

Path length is a key element for optical detectors as it ultimately determines the signal intensity and the limit of detection [36, 42]. Sensitivity increases by increasing path length of the flow cell [43] but after certain path length the intensity of light decreases and sensitivity starts to drop [44, 45]. Therefore, it is important to optimise the path length to obtain the best performance of the flow cell. Photometric detectors with different optical path lengths of 7.5, 10, 12.5 and 15 mm were printed, which had measured average path lengths of 7.47, 9.98, 12.47 and 14.98 mm respectively. These cells were evaluated using the approach discussed in 3.2.1. Fig.4 shows the sensitivity vs absorbance plot for the different flow cell lengths. From these data, the effective path length was determined to be 5.82 mm (78.0 %), 8.9 mm (90.5 %), 9.3 mm (75.0 %) and 8.4 mm (56.1%) for the 7.5, 10, 12.5 and 15 mm channel lengths respectively, which are comparable to literature values reported for other systems [4, 5, 31, 33, 36-40]. The sensitivity was found to be in the range of 10808 to 17020 AU.L/mol. for the 7.5 to 15 mm path length. Again, the sensitivity values obtained using the newly printed flow cell are ~ 20 time better than the previously reported work on 3D printed photometric detection assembly. For the presented photometric cells, the percentage of

effective path length increases when the detection path increases from 7.5 mm to 10 mm, but decreases when the channel length exceeds 12.5 mm. This decrease in the percentage of effective path length above 10 mm is possibly because of decreased light intensity at such large path length. Therefore, these results show that a path length of 10 mm has an optimum effective path length with a maximum effective path length of 90 %. These results with the obtained value of 90 % effective path length in optimized flow cell also demonstrate that the transparent window is not very much affected by the layer-by-layer printing process.

The % stray light was calculated to be in the range of 0.1 to 0.3 % for the 7.5 to 15 mm channel lengths, again superior to our previously reported 3D printed photometric detector, and is in good agreement with other reported stray light values (0.6-50%) [36, 38-40]. The reported effective path length and stray light agree with the measured noise level of the photometric detectors, tabulated together with corresponding detection limits in table 2. These results showed that the LOD decrease by increasing the path length up to 10 mm. However, above this path length there was an increase in LOD which could be because of decreased light intensity at such large path length, thus showing 10 mm as the optimum path length with maximum light intensity for the 3D printed flow cell. It must also be noted that for noise values the difference between the two smallest windows is relatively small and therefore the small difference in the determined corresponding level of noise can be regarded as acceptable. Importantly, for the larger windows, the noise levels determined follow an expected trend with decreasing levels of noise for larger windows because of higher levels of light through the larger windows. The performance of the 3D printed flow cell is comparable to literature values reported for similar detection systems machined using conventional manufacturing approaches. [4, 33, 36-39, 41, 46].

After considering all the optimising parameters, the performance of the flow cell with 10 mm path length and 500 μ m slit was found to be the best of the flow cells characterized in this work and was 80% more sensitive than poorest performing photometric flow cell. The sensitivity of the flow cell was improved by a factor 20 compared with our previously work [4]. This higher sensitivity can be attributed to the flow cell design with extended path length (10 mm) contributing to reducing the stray light by increasing the distance between the light source, i.e. LED and photodiode thus minimising the chance of any ambient to reach the detector. Furthermore, flow cell design also allows a direct contact of the flow channel with the photometric detection components in comparison to the commercial instruments that require external tubing or capillaries with limited path length, usually 0.5-500 mm, to be used. Previous reports have also shown that the sensitivity of detection can be significantly improved by directly coupling the detector with the tubing/capillary. For example, Betteridge et al [47] have been able to achieve detection of metal ions at ppb level by

using a photometric detector connect to FIA system by push-fitting flow tubing, the path-length was kept at 3 cm. Furthermore, similar configurations for nitrate/nitrite analysis provided the noise levels as low as 8×10^{-4} for a 2-cm cell [48]. [4]

4. Conclusion

Herein, the potential of multi-material 3D printing was explored to fabricate a novel photometric flow cell design which consisted of integrated channel along with cavities for LED and photodiode and incorporates a visibly transparent material in an otherwise opaque embodiment to allow for the light to travel between light source and detector. Simultaneous printing of functional components of variable properties facilitates integration of various parts into a single object, hence providing opportunities to minimise assembly parts and introduce automation. Additionally, the simplicity of design and fabrication suggest that multi-material 3D printing may provide a low-cost and flexible way to construct and integrate photometric detection in instrumentation used for chemical analysis. This study demonstrates the capability of 3D printing to fabricate photometric flow cells with complex features, such as transparent detection window within an opaque body, with an utmost simplicity that is not comparable to existing manufacturing approaches.

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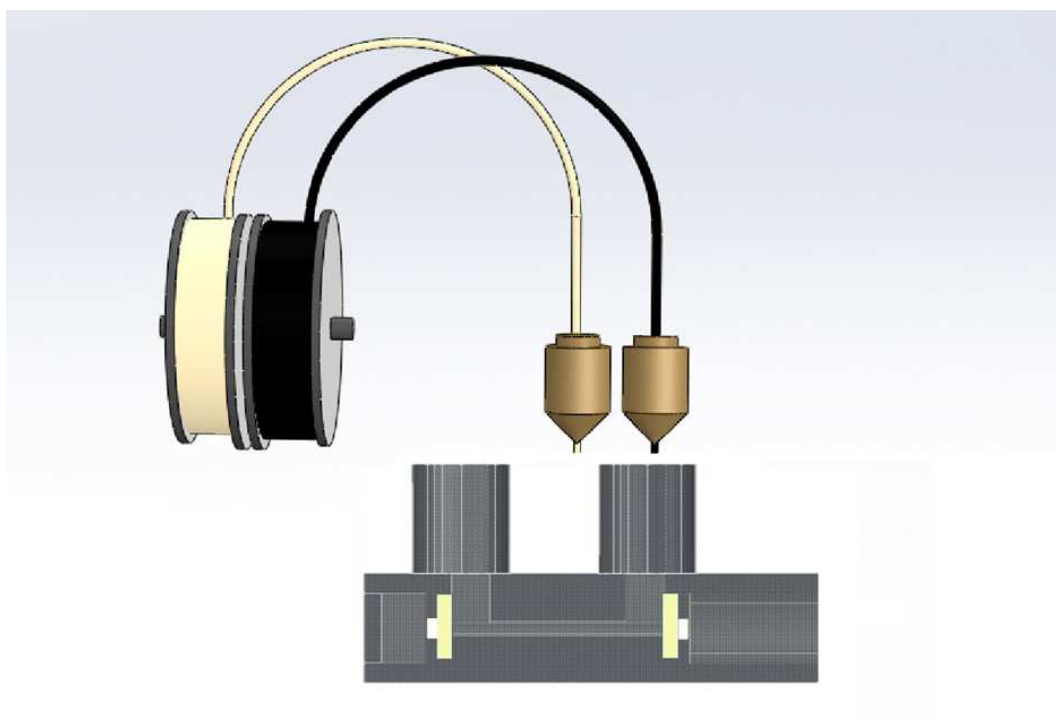
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472 **Figures:**

473 Graphical Abstract



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477 Fig.1

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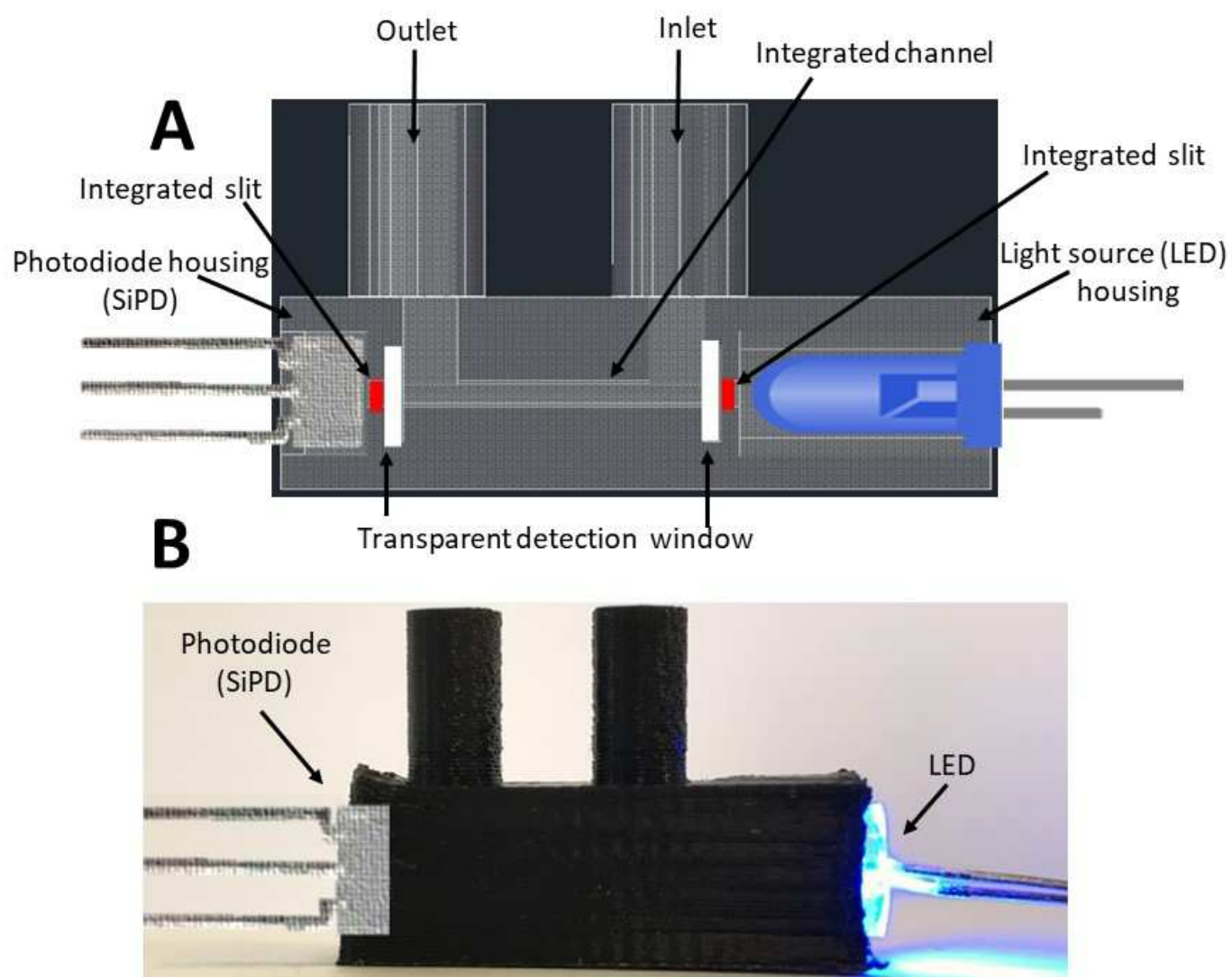
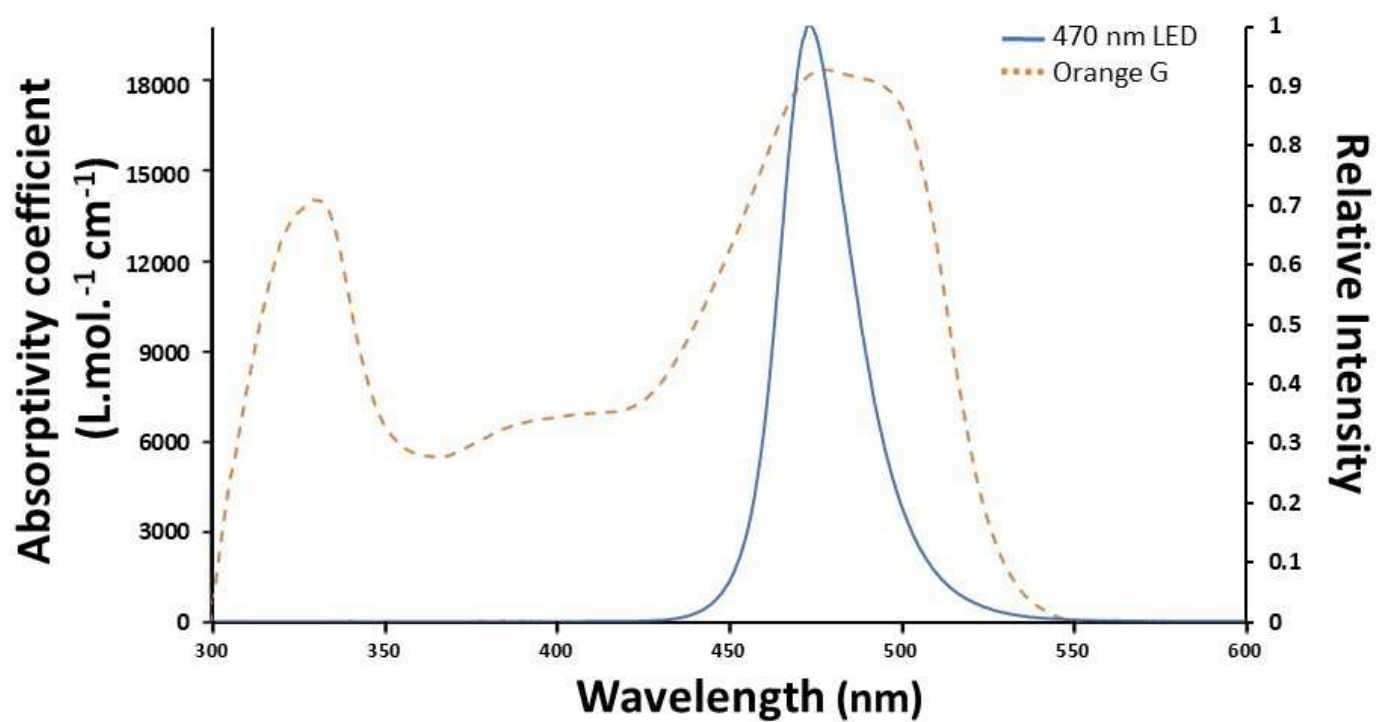


Fig.1. A) CAD design of the detector flow cell and illustration of its different parts.

B) 3D printed photometric detector flow cell

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480 Fig.2

481 Fig.2. Superimpose of the absorption spectrum of Orange G and emission spectrum of blue 470 nm LED
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485 Fig.3

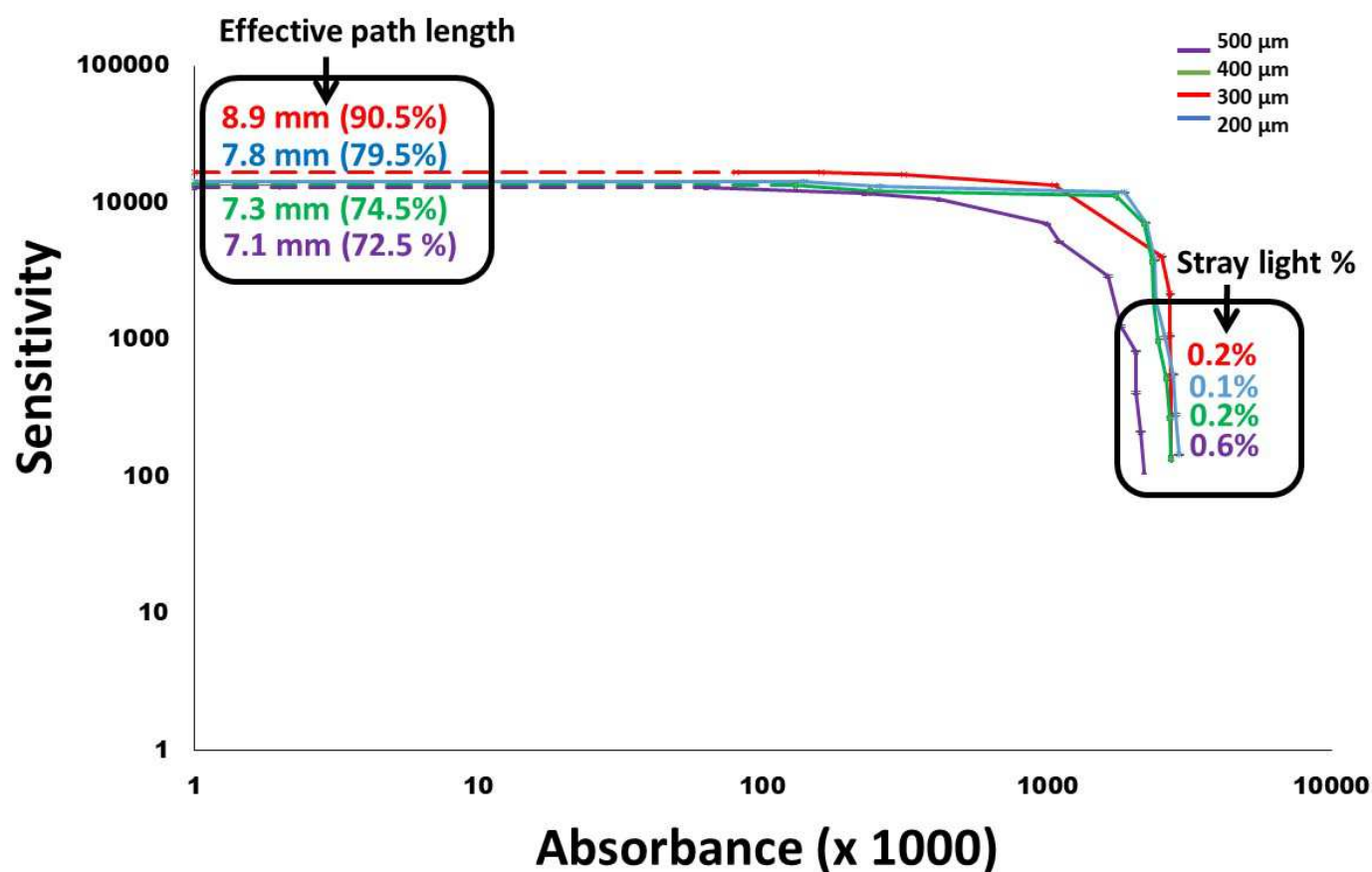


Fig.3. The plot of detection linearity depicted as a sensitivity vs absorbance graph. The average channel length of each flow cell after 3D printing ($n=3$) is 9.98 mm and the slit sizes ranges from 200 to 500 μm in examined cells. The test analyte was Orange G (measured molar absorption coefficient = $18546 \text{ L}\cdot\text{mol}^{-1}\text{cm}^{-1}$).

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487 Fig.4

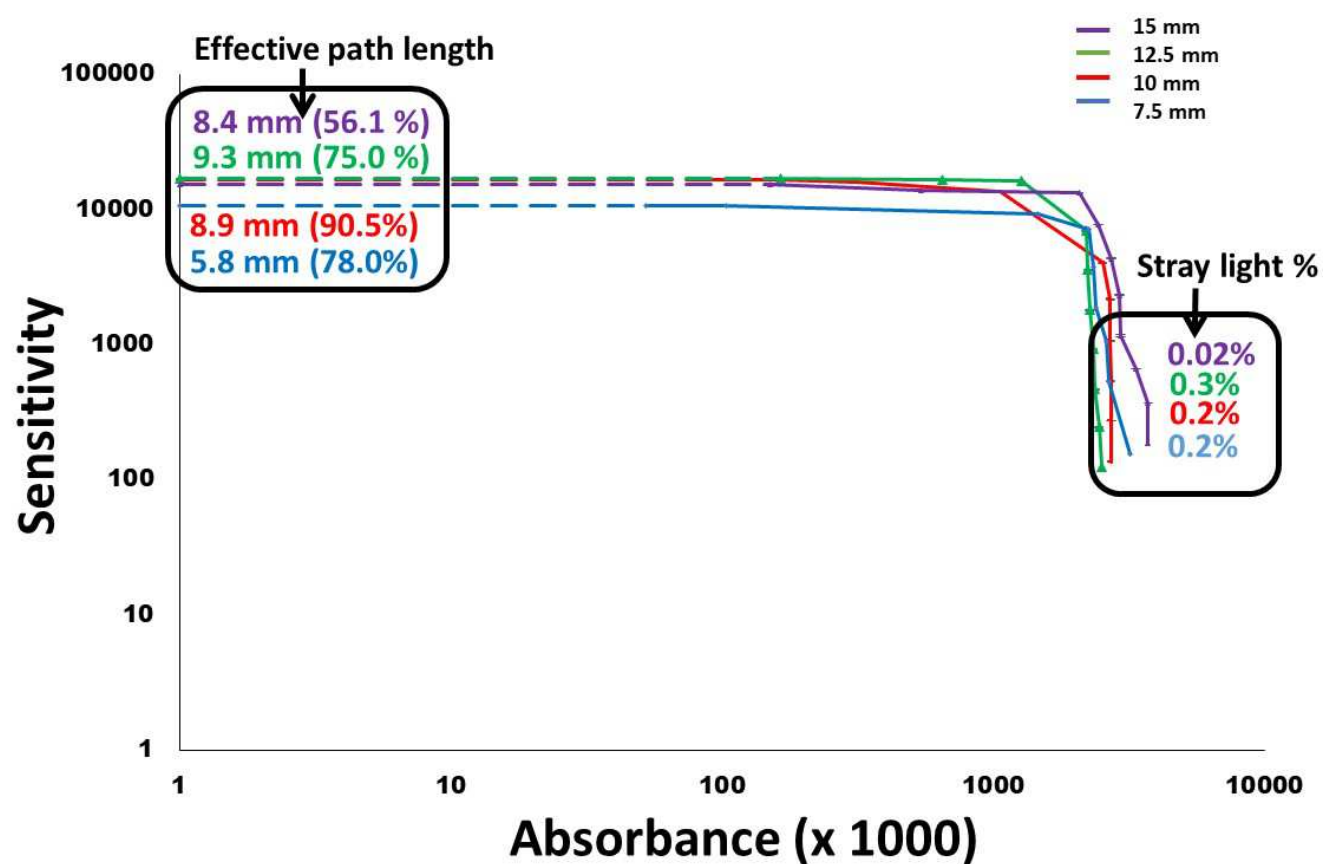


Fig.4. The plot of detection linearity depicted as a sensitivity vs absorbance graph. The size of the slit is 500 μm in all the flow cells. The average channel length, 7.47, 9.98, 12.47 and 14.98 mm (designed path length 7.5, 10, 12.5 and 15 mm respectively), for each 3D printed flow cell was used for performing the calculations. Orange G, molar absorption coefficient measured to be $18546 \text{ L}\cdot\text{mol}^{-1}\text{cm}^{-1}$, was used as the test analyte.

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Table 1. LOD, noise, and signal to noise (S/N) ratio calculated for orange G (0.0097 mM) using 3D printed photometric detector flow cell with various slit sizes (path length = 10 mm designed)

Slit size	200 μm	300 μm	400 μm	500 μm
Noise	0.40	0.26	0.18	0.011
s/n	320	490	800	15000
LOD (μM)	0.091	0.059	0.036	0.0020

491 Table.1

492

493 Table.2

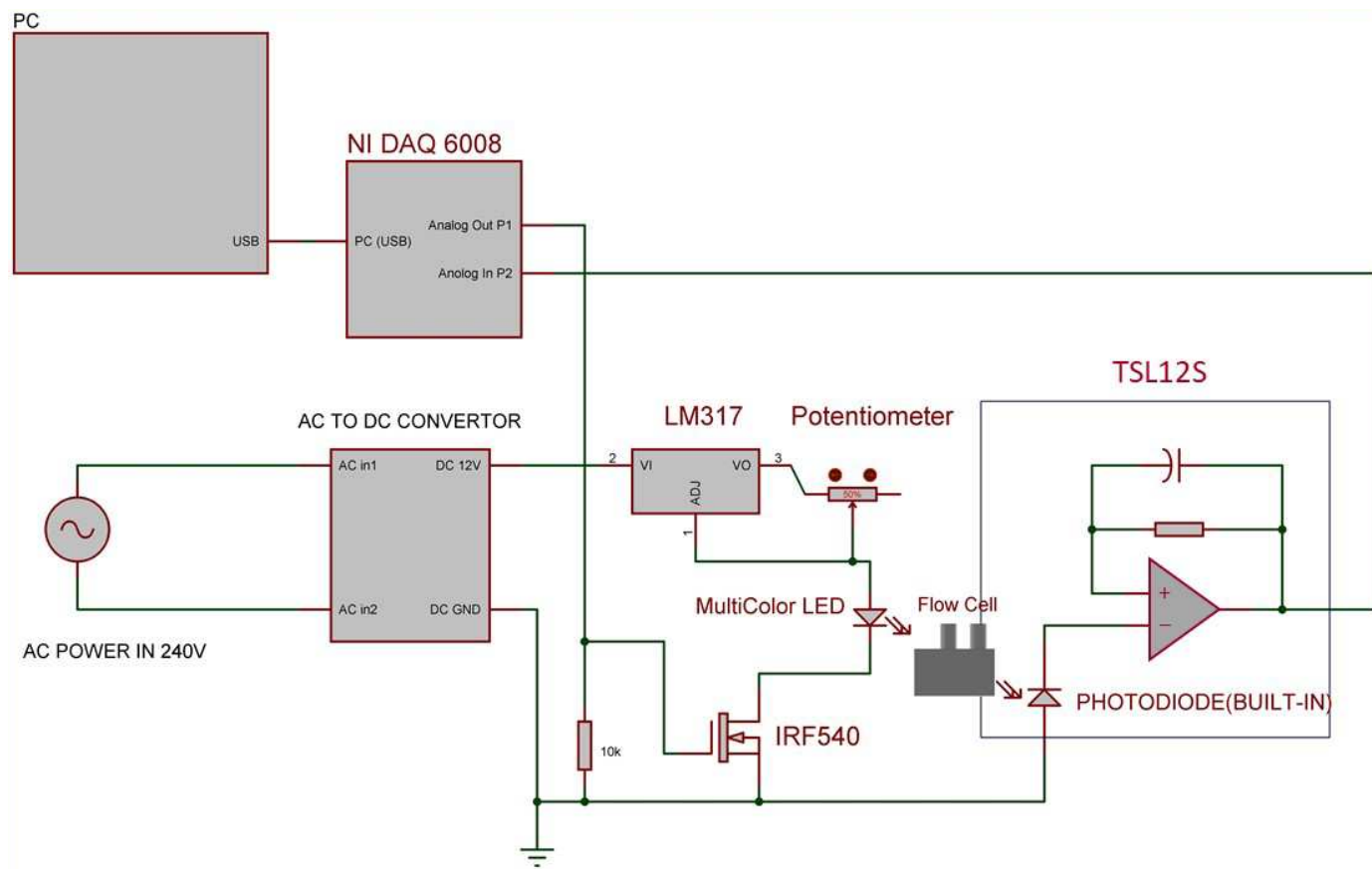
Table 2. LOD, noise, and signal to noise (S/N) ratio calculated for orange G(0.0097 mM) using 3D printed photometric detector flow cell with various pathlengths designed (slit size = 500 μm)

Path length	7.5 mm	10 mm	12.5 mm	15 mm
Noise	0.012	0.011	0.021	0.030
s/n	8700	15000	7875	5000
LOD (μM)	0.0033	0.0020	0.0037	0.0058

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495 **Supplementary information:**

496 Figure.S.1



500 Figure.S1. Circuit diagram

Figure.S.2

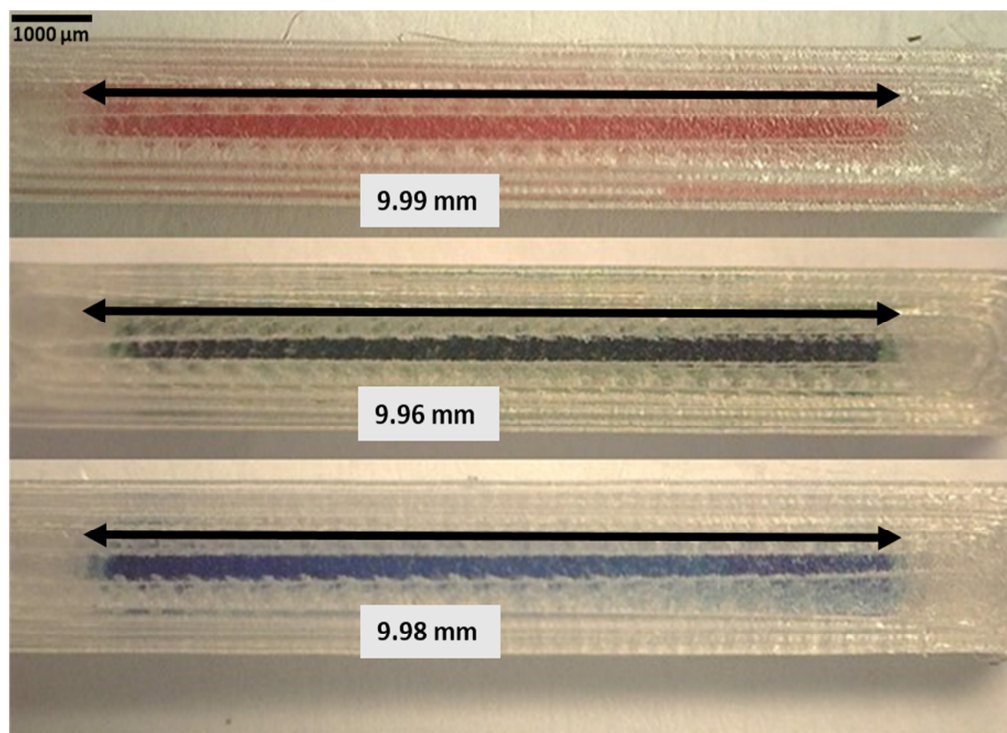


Figure. S.2 Photographic images of the 3D printed pathlength, designed pathlength= 10mm (CAD design), the printed channel length is shown using different dyes.

525 Table.S1

Table.S1. Comparison of designed vs measured pathlengths for the 3D printed flow cells (Average, $n=3$), channel was filled with a coloured dye to observe the length of the flow cells under the microscope.

Designed path length (mm)	3D printed path length (mm)	%RSD
15 mm	14.9	0.067
12.5 mm	12.4	0.081
10 mm	9.98	0.15
7.5 mm	7.47	0.28

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527

High lights

- Rapid manufacturing of photometric detector flow cell by multimaterial 3D printing
- Fabrication of integrated channel, slit and detection window in a single piece
- Incorporation of a transparent window within the opaque detection body
- Optimization and characterization of photometric detection flow cell designs
- Excellent performance in terms of % stray light, effective path and sensitivity was achieved

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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